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A comparison of gel fuels with alternative cooking fuels

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Abstract
A range of gel fuels was tested in a range of appliances designed for the fuels. The tests comprised the determination of the efficiency of the fuel/appliance combination when boiling water at full and, where possible, minimum power; and the measurement of CO, CO_2 and unburned hydrocarbons collected in a hood at the burner level in normal operation. The tests were repeated with paraffin-fuelled appliances, LP gas appliances and an electric stove. In the majority of cases it was found that the gel fuels did not meet an emission standard of a $CO:CO_2$ ratio of <0.02, and that they gave off excessive unburned hydrocarbons. It was suspected that this had to do with the mixing of the fuel vapour with air, because tests with pure ethanol in various appliances gave similar results. Tests in which appliances were modified to improve the air/fuel mixing showed that the hypothesis was valid. A subsidiary finding of the tests was that some gel fuels had excessive water, and that in these cases the condensation of the water vapour on the base of a cooking pot was so extensive that it could extinguish the flame. This leads to a recommendation that a standard for gel fuels be established. A comparison of the cost of cooking a standard meal suggests that gel fuels are unlikely to meet user's needs even if improved appliances can be developed.

Keywords: gel fuel, fuels, efficiency, emissions, cooking

1 Introduction

Gel fuels have excited a lot of interest as possible alternatives to paraffin or LP gas as fuels for cooking. This is largely because the most popular fuel, paraffin, has been shown to present considerable hazards when used in typical, readily available cookers. Our studies (Lloyd, 2006) have shown that, in use, the paraffin in the fuel tank of the wick-type of stove becomes heated to above its flash point. When that happens, the fuel can conflagrate at a rate sufficient to raise the temperature in a typical low-income home to over 400 deg C within 30 seconds. About 100 000 homes are destroyed this way every year. The Department of Minerals & Energy convened a workshop in late 2004 into the use of gel fuels, and has since encouraged the introduction of these fuels (le Roux, 2004). The gel fuel does not spill readily, and can be made from renewable resources, so may well be an improvement over the widely used paraffin. However, there have been no rigorous comparisons of the various fuels. This paper aims to make good that lack.

Figure 1: Samples of most of the fuels tested

2 Experimental

A wide range of fuels was acquired from retail sources. Most of those tested are shown in Figure 1. The calorific values of several typical gel fuels were determined by a certified analytical laboratory.

The market was scoured for examples of stoves designed to use either ethanol or ethanol gels. Few were branded, and many were designed to burn at a single heat level. Details of these appliances can be provided on request. Some stoves were prototypes, details of which are not available.

Tests comprised boiling about 1.5*l* of water and determining the time to heat from 20 deg C to boiling; determining the rate of evaporating water and the rate of consumption of fuel while boiling at various heating levels to derive the efficiency of the fuel/stove combination; collecting the combustion products in a hood and analysing them with a combustion analyser to find the $CO:CO_2$ ratio and level of unburned hydrocarbons. The cooking tests involved boiling 1*l* of water, adding 600 g of maize meal, boiling for 5 minutes and simmering for 30 minutes, to find the fuel used.

3 Results

3.1 Calorific value

The results of the determination of the calorific values of three gel fuels are given in Table 1.

Table 1: Gel fuel calorific values

	Gross CV (MJ/kg)	Net CV (MJ/kg)
Sun gel	18.7	16.1
Enviro-Heat	18.6	16.0
Bio-Heat gel	17.7	15.3

3.2 Time to boil

To determine the time to boil accurately, it was necessary to record the temperature in the pot every minute while stirring, and then to extrapolate or interpolate to 20 deg C and extrapolate to 100 deg C after fitting a quadratic or cubic equation to the data (Figure 2).

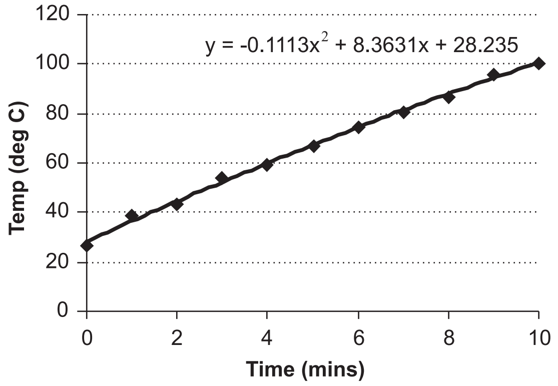

Figure 2: Determination of the time to boil

Cubic equations were often necessary to fit the results because water condensed on the bottom of the pot during the early phases of heating. Sometimes this water was so extensive that it extinguished the flame.

The results were correlated against the net power delivered to the cooking utensil (Figure 3), where the power was determined in the tests described in the next section.

The relationship was best described by a logarithmic fit, which brought together the results for all fuel and cooker combinations.

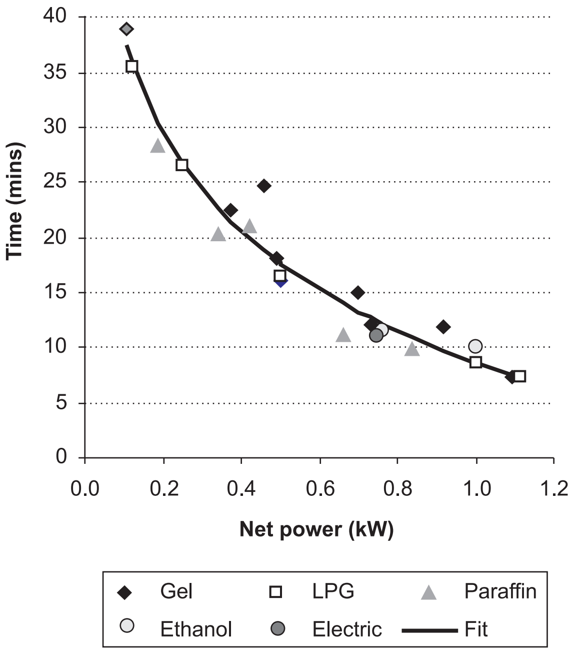

Figure 3: Correlation of the time to boil vs. net power

3.3 Efficiency

The efficiency was determined by measuring the rate of water loss and fuel consumption (Figure 4). The rate of water loss while boiling was essentially independent of the volume of water in the pot. It made no difference if the pot was covered with a lid or not. It was only slightly affected by the diameter of the pot.

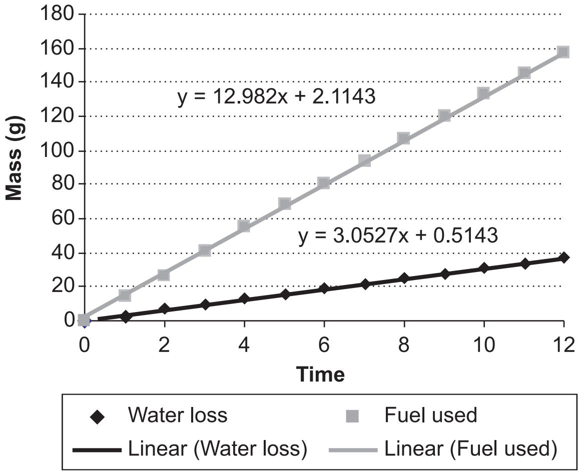

Figure 4: Determination of the efficiency

Straight lines through the data allowed the rates to be determined to an accuracy of about 1%. In the example of Figure 4, the water loss was 12.98g/minute and the fuel consumption 3.05g/minute. Then the water loss represents an evaporation energy of 2.261kJ/g water, equivalent to 2.261 x 12.98/60 = 0.489 kW. The fuel in this case was gel with a net calorific value of 16.1kJ/g, so the stove power was 16.1 x 3.05 /60 = 0.818kW and the efficiency was 0.489/0.818 = 60%.

The results for all fuel/stove combinations tested are given in Table 2, where the numbers in the first column identify the particular stove/fuel combination. Nos. 1 to 9 are all gels, 10 is electricity; 11 to 13 are ethanol liquid; 14 to 18 are paraffin and 19 is LP gas.

Table 2: Results of efficiency tests

No.	*Appliance*	*Fuel*	*Power (kW)*	*Efficiency (%)*
1	Safety Stove	Gel	0.83	45.2
2	Safety Stove, no Thermoflue	Gel	1.64	30.5
3	Cook Safe	Cook Safe	1.26 0.87	57.9 67.0
4		Sungel	0.60	13.1
5	Genius	Genius	1.22 0.78	63.2 62.8
6	Malmesbury	Clean Heat	1.22 0.60	57.5 55.0
7	Prototype I	Genius	1.79 1.52	61.3 60.3
8	Prototype II	Yellow gel	0.75	60.7
9		Genius	0.82	59.5
10	Electric	Electric	0.94 0.41	79.9 74.2
11	Origo	Meths	1.36 0.67	55.5 71.8
12		Ethanol	1.57 0.50	48.8 56.8
13	Origo (new)	Ethanol 0.55	1.53 54.1	65.3
14	Primus	Paraffin	1.14	49.3
15	Parasafe	Paraffin	0.74 0.81	56.9 41.8
16	FSP	Paraffin	1.43	58.5
17	Hippo	Paraffin	0.72	26.0
18	Panda	Paraffin	1.48 1.15 0.95	44.5 36.6 38.3
19	Cadac	LPG	1.85 0.87 0.29	60.5 58.4 38.4

Note that some appliances (e.g. Safety Stove, Prototype II, and FSP) did not permit control of heat, while both the Primus and the Parasafe had very slight control. Not reported in this table are a number of stove/fuel combinations that failed to boil 1.5*l* of water.

3.4 Emissions

The emissions tended to be greater when the appliance was operated at higher power. This is illustrated in Figures 5 and 6, in which the number of each fuel/stove combination is given in Table 2.

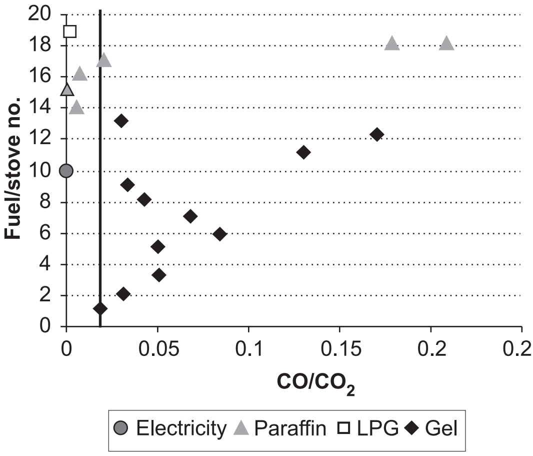

Figure 5: CO/CO$_2$ ratio at high power

At high power only one of the gels (No. 1) meets the 0.02 ratio employed in the relevant standards (SANS, 2006). The LP gas and several of the paraffin fuelled appliances meet the standard comfortably. Of note is the reduction in CO: CO$_2$ ratio between No. 12 (Origo with ethanol) and No. 13 (Revised Origo with ethanol). This is discussed in the next section.

At lower power, few of the gel-fuelled appliances improved, but the Origo met the standard before modification and was comfortably within the standard after modification. The Panda paraffin stove (No. 18) improved its performance slightly, but was still above the standard.

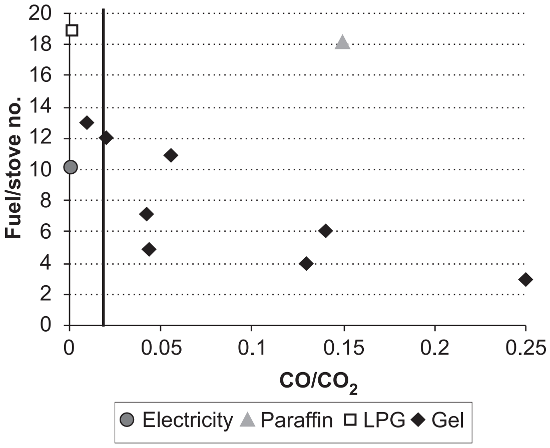

Figure 6: CO:CO$_2$ ratio at low power

The results for hydrocarbon emissions are not reported here, but were very similar to those for CO. High CO emissions were invariably associated with high hydrocarbon emissions. Even nominally clean fuels, such as chemically pure ethanol, burned smokily in some appliances. Figure 7 shows a pot, which was used once to boil water with pure ethanol as fuel, blackened in comparison with a pot that had been used several times with paraffin as fuel.

Figure 7: Pot on right blackened after boiling water once using ethanol fuel in a prototype cooker

3.5 Cooking

The results of the cooking tests are summarised in Table 3, arranged in order of the mass of fuel used to cook the standard meal. The figures are somewhat misleading, because cooking the porridge for 5 minutes after adding the maize meal to the boiling water burned the porridge in the case of the LPG and electric stove tests. In practice, the stoves would be put into simmer mode immediately after mixing. The energy required for cooking with LPG and electricity is therefore overstated in Table 3. It took between 41 and 49 minutes to cook, so there was little impact of higher power and rapid boiling. The ability to simmer effectively had a far greater impact on the energy consumed in cooking and the total cost.

Table 3: Results of cooking tests

Stove	*Fuel*	*g of fuel used*	*LHV (kJ/kg)*	*kJ to cook*	*Cost to cook (R)*
Prototype I	Gel	209	16100	3491	1.78
Genius	Gel	144	16100	2332	1.22
Origo	Ethanol	95	22210	2110	0.90
FSP	Paraffin	67	44267	2966	0.50
Primus	Paraffin	65	44267	2877	0.48
Panda	Paraffin	56	44267	2479	0.42
Parasafe	Paraffin	49	44267	2169	0.36
Cadac	LPG	43	46139	1984	0.41
Electric	Electric			1438	0.20

4 Discussion and conclusions

The results given in Table 1 show that the gel fuels have a surprisingly low lower heating value (LHV). The presence of even small quantities of water has a considerable impact. We derived as a simple model for the effect, which reproduced the data of Table 1 assuming the Sun and Enviroheat gels, each had nearly 70% ethanol by weight and the Bioheat had only 65%.

The accurate determination of the time to boil was found to be quite difficult. All manner of variables had to be carefully controlled to obtain reasonably consistent and reproducible results – for some cookers even the positioning of the pot had an effect. Some fuel-cooker combinations gave large quantities of smoke, and soot built up on the pot during the test, changing the heat transfer characteristics. Some fuels gave off large quantities of water, which condensed on the pot until the contents reached about 60 deg C. This meant that between about 20 and 60 deg C the fuel was yielding the higher heating value, and only achieved the lower heating value above 60 deg C. As noted previously, for some fuels the condensation on the pot was so extensive that the flame could be extinguished. Some of the gel fuels burned at increasing rates the longer they burned, which, we believe, are why cubic equations were necessary to fit the observations in some cases. Quadratic equations were always needed because heat losses from the pot obviously increased as the pot became hotter, and because one of those losses is water driven off from the pot as it approaches boiling.

We mention these because the time-to-boil is often used to determine the efficiency. As Figure 3 shows, there is a unifying correlation between the net power and the time-to-boil, but even with considerable care being taken, there is a large amount of scatter, which means that there would be large errors in the determination of the efficiency.

If we consider the efficiency results in Table 2, the gel fuels gave reasonably good efficiencies in the order of 60%. The CookSafe stove was designed to use a special liquid fuel, so it is not surprising that it gave very poor results with the Sun gel. Some idea of the accuracy and reproducibility of this type of efficiency measurement can be gauged from the comparison of the two results for the Prototype I stove, which gave essentially the same efficiency when operated with the same fuel at slightly different power outputs; and the Prototype II, when operated with different fuels at similar power outputs.

The electric stove gave a very high efficiency of close to 80%. The slightly lower efficiency at lower power appeared to be due to the cycling of the control. Power flowed to the element for 13 seconds out of every 30. When it started, the element was cold, the resistance was low and the element gave reduced power. Within a few seconds the element had warmed up and delivered its full power.

The ethanol-fuelled Origo gave varied results. Initially it gave relatively poor performance at high power, which improved at lower power. The developers carried out modifications, and the new Origo gave over 60% efficiency at high power, comparable with the gels.

The paraffin fuelled appliances generally gave poorer efficiency than the gels. This is believed to be due to the appliance losing more heat than in the case of the gel fuels. In the wick stoves, significant quantities go into heating the shrouds round the burner, which have to be raised to red heat to evaporate paraffin from the wick. In the case of the Primus-type, the flame first plays on the chamber where paraffin is turned to vapour and only after that heats the pot. There may also be an effect due to the temperature of the flame being higher than that of the alcohol flame, with greater heat losses round the sides of the pot. However, the achievement of over 60% efficiency with the LP Gas suggests that the effect of flame temperature is probably small.

Figure 1 shows that to boil in less than 10 minutes requires about 0.7kW net power. This suggests that if the efficiency is about 50%, then the appliance needs a maximum output of 1.4kW, and at 60% efficiency about 1.2kW. Many of the gel-fuelled appliances fall within this envelope; comparatively few of the paraffin-fuelled ones achieve this.

The LP gas cooker is, if anything, overpowered according to this standard – as Figure 3 shows, it achieved the fastest boil.

The performance of the Safety Stove was most interesting. This was merely a can of fuel with a patented Thermoflue, comprising an expanded metal cover with a short (15 mm) chimney at its centre that fitted over the top of the can. With the Thermoflue present, it had a relatively low power and moderate efficiency. Without the Thermoflue it had double the power and much lower efficiency.

The results for emissions in Section 3.4 identified a major disadvantage of gel fuels. At its most simple, there are two types of flame – diffusion-type flames such as those of a candle, and mixed air-fuel flames. It is, almost by definition, impossible to mix gel and air, so the gel stoves operate primarily by diffusion. Diffusion flames tend to burn slower and to produce more soot than premixed flames because there is not sufficient oxygen for the reaction to go to completion. At higher power, there is a greater fuel flow, and the effects of poor mixing are greater.

The same design fault was present in the Origo. In its initial format, the cooker produced copious quantities of soot. It was suggested that this might be due to the presence of some of the denaturants in the methalated spirits employed, but the generation of soot was just as bad when chemical-grade ethanol was used. The developers modified the design to improve the fuel-air mixing, and were successful, as the data for points 12 and 13 in Figure 5 show.

This also was clearly the origin of the benefits of the Thermoflue used with the Safety Stove. It reduced the fuel flow (lower power) and drew in air through the grid, giving the flame more of a mixed-flame characteristic (compare points 1 and 2) in Figure 5.

Many of the paraffin appliances gave low emissions. It came as something of a surprise that the emissions from the Panda were as high as they were. This is one of the most popular of the paraffin cookers. Not only was the CO/CO_2 ratio about ten times the SANS limit of 0.02, but the hydrocarbon emissions were at least ten times those of other paraffin cookers.

LP gas was extremely clean burning, and indeed seems to be the standard against which other cookers should be judged.

The cooking tests showed that it is essential for a cooker to be able to both boil rapidly and simmer at low heat. The Genius stove used two-thirds of the fuel used by the Prototype I because the Prototype I had very limited lower-power capability. The Parasafe used three-quarters of the fuel of the Primus because, although both had no turndown, the Parasafe was inherently lower power, and even though cooking took significantly longer (49 vs. 43 minutes for the Primus) it used less energy. The LP gas cooker used least fuel of all, even though it was overstated in these tests, because its power could be reduced to very low levels during simmering.

We would conclude as follows:

1. The gel fuels have very little promise of providing a satisfactory solution to the problem of cooking safely, largely because they burn with the release of significant quantities of pollutants due to the flame being inherently diffusive.
2. The gel fuels have the additional problem that they carry much less energy than the alternative fuels, so cooking a standard meal requires about three times more gel than the mass of alternative fuels. This means that they need to cost about one-third of the alternative fuels to be competitive, and there are no signs that they can be marketed at this price level.
3. The ideal cooker needs to be able to deliver about 0.7kW to the pot, which implies a peak power output of around 1.4kW for a paraffin-fuelled device.
4. The ideal cooker also needs to be able to have the output power reduced to the order of <0.5kW to allow simmering without excessive fuel consumption.
5. The ideal cooker should not use significant quantities of heat to vaporize the fuel to permit premixing with air. The Primus and similar devices have the additional disadvantage that the temperature of the vaporization chamber is sufficient to char the fuel, which leads to char particles blocking the jet.
6. Reducing the heat needed to vaporize the fuel would reduce the quantity of secondary fuel required to preheat the Primus-type of burner.
7. Whatever appliance finds its way into the South African market needs to comply with the requirements of the revised SANS 1908 and 1243. There are at present about 1 million cook-

ers using liquid fuels that find their way into the South African market every year. Those cookers need to be safe if the problems that have been observed with existing appliances are not to be repeated. The new standards go a long way to ensuring that the appliances will indeed be safe.

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